

Spin-current diode with a ferromagnetic semiconductor

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Diode is a key device in electronics: the charge current can flow through the device under a forward bias, while almost no current flows under a reverse bias. Here we propose a corresponding device in spintronics: the spin-current diode, in which the forward spin current is large but the reversed one is negligible. We show that the lead/ferromagnetic quantum dot/lead system and the lead/ferromagnetic semiconductor/lead junction can work as spin-current diodes. The spin-current diode, a low dissipation device, may have important applications in spintronics, as the conventional charge-current diode does in electronics.

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A new subdiscipline of condensed matter physics, spintronics that exploits electron spin to replace the role of electron charge in electronic devices, is emerging rapidly and generating great interests in the last decade.¹⁻³ Some interesting effects, such as the giant magnetoresistance phenomena,^{4,5} (quantum) spin Hall effect,⁶⁻¹¹ and persistent spin current¹²⁻¹⁴ have been discovered. They received a lot attention and even generated great applications. Based on the spin degree of freedom of electron, many electronic devices have been proposed, such as the magnetoresistance device,^{1,2,4,5,15,16} the Datta-Das transistor,^{17,18} spin valve,^{19,20} spin filter,²¹⁻²³ spin-polarized current generator, pure spin-current generator^{8,24-27} and spin diode device.²⁹⁻³³ Many above-mentioned devices (e.g. the Datta-Das transistor,¹⁸ spin filter,^{21,22} spin-current generator,^{8,24-27} etc.) have been successfully realized in experiments. Some extensive practical applications have also been achieved. For example, the magnetoresistance devices have been extensively applied in various commercial electronic products nowadays and generated huge commercial values.^{4,5}

On the side of the charge degree of freedom of an electron, a very important electronic device is the diode: the charge current can flow through it under a forward bias but the current is tiny under a reverse bias. In the last century, various (charge-current) diodes have been successfully made.²⁸ The diode is a key device in electronics and it has been extensively used in almost all electronic products and instruments.²⁸ A natural question is whether there exists a counterpart to the charge-current diode on the side of the spin degree of freedom. It means that a device has such a characteristic: a large spin current can flow through the device under a forward spin bias, while under a reverse spin bias the spin current is very small. We name this device the spin-current diode, which should have great applications in the future high-operating-speed and energy-saving spintronic products. It also merits a mention that some previous works have proposed and investigated the spin diode,²⁹⁻³³ e.g. in the system consisting of normal-metal lead/quantum dot (QD)/ferromagnetic (FM) lead, both theoretically^{30,31}

and experimentally.^{32,33} The spin diode in these previous references²⁹⁻³³ are devices in which the charge current or its spin polarization are strongly asymmetric for the forward and reverse biases, utilizing electron spin degrees of freedom. Thus, they are still devices dealing with the charge current. Therefore, the spin-current diode proposed here is completely different from the spin diode studied before, and it has never been explored before.

In this Letter, we propose a spin-current diode, which consists of a normal lead/FM semiconductor (or FM QD)/normal lead. Fig. 1(a) shows schematically the device, consisting of the spin-current generator, spin-current diode and spin-current detector, in three dotted-line rectangles, respectively. The spin-current generator and detector which consist of the FM electrodes weakly coupled to normal-metal leads, have successfully been realized in recent experiments.^{8,25-27} Here we use them to generate the spin current (i.e. as a spin bias) as well as to detect the spin current. In the middle rectangle in Fig. 1(a), it is the spin-current diode proposed in the present letter, in which a large spin current flows through it under a forward spin bias but the spin current is quite small for the reverse spin bias, and the charge current is zero always. Let us first discuss why the device can work as a spin-current diode. For a FM semiconductor with a FM magnetization M , the conduction band and valence band will be spin-resolved as shown in Fig. 1(b) and (c). Here the highest valence band and the lowest conduction band are usually spin opposite and there is a gap between them. The FM semiconductor has been extensively studied in the last three decades, and various FM semiconductors, such as GaMnAs and InMnAs, have been found.³⁴⁻³⁷ Considering a spin bias acts on the lead/FM semiconductor/lead junction, the chemical potential of the left lead is spin-resolved,³⁸ due to the spin-current generator on the left side as shown in Fig. 1(a). For the forward spin bias, the spin-up chemical potential $\mu_{L\uparrow}$ is larger than the spin-down one $\mu_{L\downarrow}$ [see Fig. 1(b)]. It can drive the spin-up electrons flow from the left lead through the FM semiconductor to the right lead and the spin-down electrons flow in the reverse direction, leading a large forward spin current. On the other hand, for the

reverse spin bias, $\mu_{L\uparrow} < \mu_{L\downarrow}$ [see Fig. 1(c)], the spin-down (spin-up) electrons can hardly tunnel from the left (right) lead to the middle FM semiconductor. This is because there is no spin-down (spin-up) band in the spin-bias window, so that the spin current with the reverse spin bias is very small. Furthermore, we will also show that the device of lead/FM QD/lead can have the similar function as that of the lead/FM semiconductor/lead, and both of them can work as the spin-current diodes.

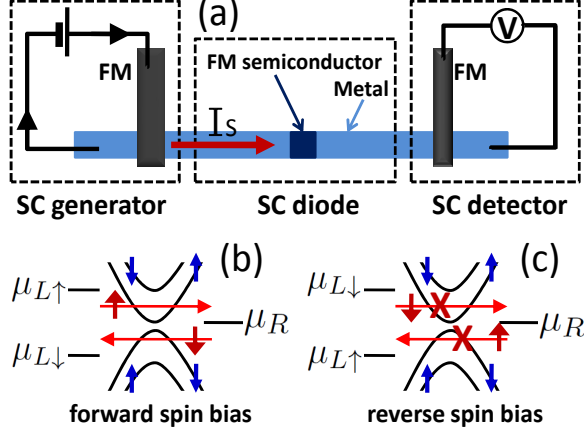


FIG. 1: (Color online) (a) The schematic diagrams for the spin-current generator, the spin-current diode and the spin-current detector. Here the device in the middle dotted box is the spin-current diode proposed in this article. (b) [(c)] schematically shows that the spin current can (can not) flow through the lead/FM semiconductor/lead junction under the forward (reverse) spin bias.

We first study the spin transport through the lead/FM QD/lead device, whose Hamiltonian is:

$$H = \sum_{\alpha,k,\sigma} \epsilon_{\alpha k} a_{\alpha k \sigma}^\dagger a_{\alpha k \sigma} + \sum_{\sigma} (\epsilon_d - \sigma M) d_{\sigma}^\dagger d_{\sigma} + \sum_{\alpha,k,\sigma} \left(t_{\alpha} a_{\alpha k \sigma}^\dagger d_{\sigma} + H.c. \right), \quad (1)$$

where $a_{\alpha k \sigma}$ ($a_{\alpha k \sigma}^\dagger$) and d_{σ} (d_{σ}^\dagger) are the annihilation (creation) operators of electron with spin σ ($\sigma = \uparrow, \downarrow$) in the lead α ($\alpha = L, R$) and the QD, respectively. The QD has a single energy level ϵ_d with the spin splitting energy M due to the FM magnetization or the Zeeman effect of an external magnetic field. By using the non-equilibrium Green's function method, the particle currents from the left lead through the QD to the right lead are:^{39,40}

$$I_{\sigma} = (1/\hbar) \int (d\epsilon/2\pi) T_{\sigma}(\epsilon) (f_{L\sigma} - f_{R\sigma}). \quad (2)$$

Here the transmission coefficient $T_{\sigma}(\epsilon) = \Gamma_L \Gamma_R / [\epsilon - \epsilon_d + \sigma M]^2 + \Gamma^2/4]$ with the linewidth function $\Gamma = \Gamma_L + \Gamma_R$, $\Gamma_{\alpha} = 2\pi \rho_{\alpha} |t_{\alpha}|^2$ with ρ_{α} being the density of state of the lead α . The Fermi-Dirac distribution $f_{\alpha\sigma} = 1/\{\exp[(\epsilon - \mu_{\alpha\sigma})/k_B T] + 1\}$ at temperature T . After obtaining the

particle current, the spin current $I_s = (\hbar/2)(I_{\uparrow} - I_{\downarrow})$ and the (charge) current $I_e = e(I_{\uparrow} + I_{\downarrow})$ can be calculated straightforwardly. Considering the action of the spin bias V_s , the chemical potentials of the left lead $\mu_{L\uparrow} = -\mu_{L\downarrow} = eV_s$ is spin-resolved,³⁸ but that of the right lead $\mu_{R\uparrow} = \mu_{R\downarrow} = eV_R$ is spin-independent due to the spin-current generator in the left side as shown in Fig. 1(a). In the calculation, by considering the open circuit, the charge current I_e exactly is zero, from which the voltage V_R of the right lead can be obtained.

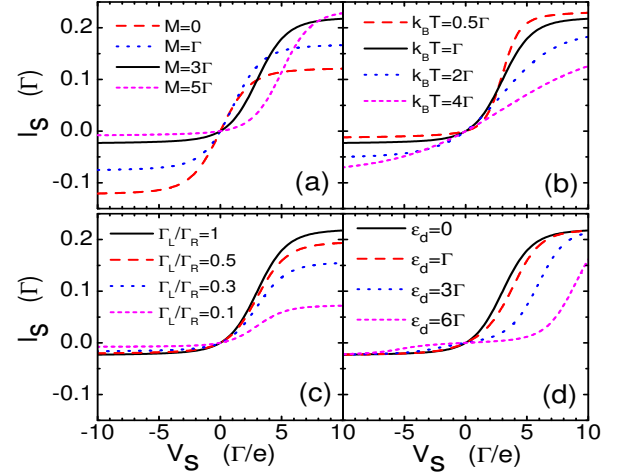


FIG. 2: (Color online) (a)-(d) show I_s vs. V_s at the different M (a), the different temperature $k_B T$ (b), the different asymmetric couplings Γ_L/Γ_R (c) and the different QD's level ϵ_d (d). If the parameters are not shown in the legends, they are $\epsilon_d = 0$, $k_B T = \Gamma$, $M = 3\Gamma$ and $\Gamma_L/\Gamma_R = 1$.

Fig. 2 shows the spin current I_s as a function of the spin bias V_s . While the spin splitting energy $M = 0$, $I_s(V_s) = -I_s(-V_s)$ regardless of the other parameters. In this case, the device does not have the diode features. On the other hand, while $M \neq 0$, the device shows the diode features, and the value of spin current I_s for the forward spin bias V_s is not equal to that of the negative V_s , i.e. $I_s(V_s) \neq -I_s(-V_s)$ [see Fig. 2(a)]. For the larger spin splitting energy M , the diode feature is more evident. For example, for $M = 5\Gamma$, the spin current can exceed 0.22Γ for the forward spin bias $V_s = 10\Gamma/e$, but it is only about -0.008Γ for the reverse spin bias $V_s = -10\Gamma/e$, and the ratio of the forward and reverse spin current is about 30. In other words, the lead/FM QD/lead device is a good spin-current diode. While M is negative, $I_s(-M, V_s) = -I_s(M, -V_s)$. This means that the polarity direction of the spin-current diode can be reserved by reserving M . For a positive M , the spin current can flow from the left side through the device to its right side and the reversed spin current can hardly flow through the device. However, for a negative M , the reverse spin current can flow through the device and the forward one can not. Compared to the charge-current diode, the ability to control the polarity direction of the spin-current is a great advantage. Notice that for the

charge-current diode (e.g. p-n junction), its polarity direction is fixed and can not be changed once the device is fabricated.

Let us discuss how the system parameters will affect the capability of a spin-current diode. With increase of temperature T , the spin current for a forward spin bias reduces but the reverse one increases, and the diode feature gradually decays as shown in Fig. 2(b). For $k_B T < M$ (e.g. $k_B T = 0.5\Gamma$ or Γ), however, the diode feature is well maintained.

So far we have considered cases that the coupling between QD and the left and right leads are symmetric with $\Gamma_L = \Gamma_R$. In an experiment, the couplings are usually asymmetric. Fig. 2(c) shows the effect of the asymmetric couplings on the diode feature of the device. When the couplings are asymmetric, both the forward and reverse spin currents fall, because the transmission coefficients reduce. However, the ratio $|I_s(V_s)/I_s(-V_s)|$ is almost kept even for very large asymmetrical couplings, e.g. $\Gamma_L/\Gamma_R = 0.1$. This means that the device's diode feature is robust against the asymmetrical couplings.

Thus far, we have set the QD's level ϵ_d at zero, i.e. right at the Fermi energy. But experimentally, the QD's level ϵ_d is controllable by the gate voltage. Now, when ϵ_d is away from zero, we find that the forward spin current at large forward spin bias and the reverse spin current at large reverse spin bias can almost maintain their values [see Fig. 2(d)], thus, the diode feature holds well. But the threshold spin bias V_s^{th} increases with the increase of ϵ_d , and V_s^{th} is roughly equal to ϵ_d . The forward spin current is small for $V_s < V_s^{th}$ and it quickly rises only when V_s is beyond V_s^{th} . Another importance message from Fig. 2(d) is that the spin current can be sensitively enhanced by adjusting the gate voltage, thus, the set-up provides the main function of a spin current transistor, in which an input charge signal at the gate voltage terminal can be changed to control the signal of the spin current.

Next, we study the spin transport through the lead/FM semiconductor/lead junction. Here we consider that the FM semiconductor has a conduction band and a valence band with the energy gap E_g and the FM magnetization M . Its Hamiltonian is:

$$H_{SC} = \begin{pmatrix} \frac{p_x^2 + p_y^2}{2\gamma_e m_0} - \hat{\sigma}_z M + \frac{E_g}{2} & 0 \\ 0 & -\frac{p_x^2 + p_y^2}{2\gamma_h m_0} - \hat{\sigma}_z M - \frac{E_g}{2} \end{pmatrix} + V(y), \quad (3)$$

where $p_{x/y} = -i\hbar \frac{\partial}{\partial x/y}$ is the momentum operator, $\gamma_e m_0$ and $\gamma_h m_0$ are the effective masses of the carriers in the conduction and valence bands with the electron mass being m_0 , and $\hat{\sigma}_z$ is a Pauli matrix. The potential $V(y) = \infty$ when $y < 0$ or $y > W$, and $V(y) = 0$ when $0 < y < W$, namely, a FM semiconductor nanoribbon with width W is being considered. The energy bands of this FM semiconductor are schematically shown in Fig. 1(b) and (c).

First, let us assume that the transport from the FM semiconductor to the lead is ballistic without the back-scattering. This assume is reasonable if the lead has much more transverse modes than that in the FM semiconductor.⁴⁰ In this case, the transmission coefficients $T_\sigma(\epsilon)$ are equal to the number of the transverse modes of the FM semiconductor. After obtaining the transmission coefficients, the spin current can be calculated as described above. In the numerical calculations, we take the ribbon width $W = 20nm$, the gap $E_g = 0.5eV$ which is a typical value for a semiconductor, and $\gamma_e = \gamma_h = 1$ (i.e. the conduction and valence bands are mirror symmetrical with regard to the Fermi energy).

Fig. 3(a) shows the spin current I_s through the lead/FM semiconductor/lead junction as a function of spin bias V_s with different FM magnetization M . While $M = 0$, $I_s(V_s) = -I_s(-V_s)$, and the rectification of the spin current is absent from the device. When the magnetization M is non-zero, the forward spin current rises under the forward spin bias, but under the reverse spin bias the reverse spin current is restrained, such that the spin-current diode feature appears. Even for a small M , the diode feature can be very pronounced. The reasons have been described above in detail.

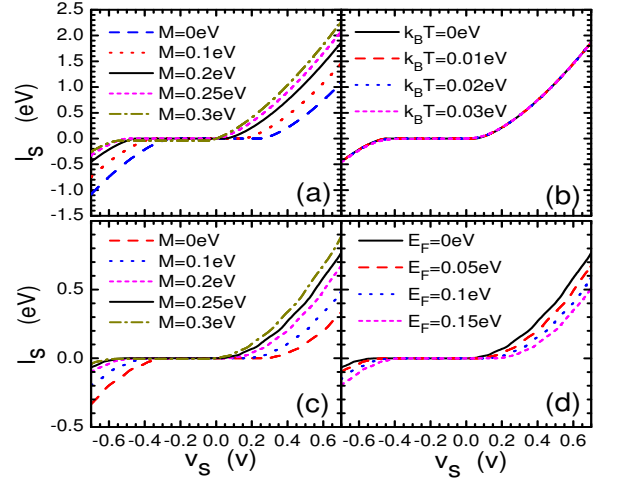


FIG. 3: (Color online) (a)-(d) show I_s vs. V_s without [(a) and (b)] and with [(c) and (d)] the interface scattering between the leads and the FM semiconductor. The FM semiconductor's gap is $E_g = 0.5eV$ and its size is with width $W = 20nm$ and length $5nm$. $k_B T = 0$ for (a), (c) and (d), $E_F = 0$ for (a), (b) and (c), and $M = 0.2eV$ (b) and $M = 0.25eV$ (d). All curves in (b) are almost overlap together.

Let us discuss the characteristics of this spin-current diode. (1) In a suitable spin bias range, the spin-current rectification of this device is almost perfect. For the spin bias in the range of $\frac{E_g}{2} - M < V_s < \frac{E_g}{2} + M$, the forward spin current is in the order of eV . However, for the corresponding reverse spin bias $(-\frac{E_g}{2} + M > V_s > -\frac{E_g}{2} - M)$, the spin current is almost zero. In this case, the ratio of the forward and reverse spin currents, $|I_s(V_s)/I_s(-V_s)|$, is approaching infinity in principle and the device works

as an ideal spin-current diode. (2) The threshold spin bias of the diode is $V_s^{th} = \max(\frac{E_g}{2} - M, 0)$, and the forward spin current appears until V_s is larger than V_s^{th} . (3) If the magnetization M is larger than $E_g/2$, the gap of the FM semiconductor is closed. In this case, the threshold spin bias is zero. Meanwhile, a small reverse spin current appears. The diode feature is still quite good [see the curve of $M = 0.3eV$ in Fig. 3(a)]. (4) As in the lead/FM QD/lead system, the spin current in the lead/FM semiconductor/lead junction also has the property, $I_s(-M, V_s) = -I_s(M, -V_s)$. So the polarity direction of the spin-current diode can be reserved by tuning the magnetization direction. Compared to the charge-current diode, this is a great advantage. (5) Fig. 3(b) shows the spin current I_s versus the spin bias with different temperature T . Due to the presence of the gap, the spin currents are almost independent of temperature. This means that the diode feature of the device can be well kept even if $k_B T$ reaches to $0.03eV$.

Second, we investigate what happens when the scattering exists at the interface of the lead and the FM semiconductor, as is the case in a practical set-up. In this case, the system can be described by the Hamiltonian $H = H_{SC} + H_L + H_R + H_C$, where H_{SC} , $H_{L/R}$, and H_C are the Hamiltonians of the FM semiconductor, the left/right lead, and the coupling between them, respectively. Here we consider the non-magnetic normal leads with their Hamiltonians $H_{L/R} = \frac{p_x^2 + p_y^2}{2m_0} + V_0$ and the potential energy V_0 . The Hamiltonian H_{SC} has been shown in Eq.(3). In order to calculate the transmission coefficients T_σ , we discretize the Hamiltonian:⁴⁰

$$\begin{aligned} H_{SC} &= \sum_{i \in SC} a_i^\dagger H_{ii}^{SC} a_i + \sum_{\langle ij \rangle} a_i^\dagger H_{ij}^{SC} a_j, \\ H_{L/R} &= \sum_{i \in L/R} b_i^\dagger H_{ii}^{L/R} b_i + \sum_{\langle ij \rangle} b_i^\dagger H_{ij}^{L/R} b_j, \\ H_C &= \sum_{i_y} (b_{0i_y}^\dagger H_{LC} a_{1i_y} + b_{N+1, i_y}^\dagger H_{RC} a_{Ni_y} + h.c.), \end{aligned}$$

where a_i^\dagger (a_i) and b_i^\dagger (b_i) are the creation (annihilation) operators in the FM semiconductor and the leads, with the discrete site $\mathbf{i} = (i_x, i_y)$. $i_x \in (-\infty, 0)$, $i_x \in (1, N)$ and $i_x \in (N+1, \infty)$ are the region of the left lead, the FM semiconductor and the right lead, respectively. $H_{ii}^{SC} = \text{diag}(\frac{E_g}{2} - M + 4t_e, \frac{E_g}{2} + M + 4t_e, -\frac{E_g}{2} - M - 4t_h, -\frac{E_g}{2} + M - 4t_h)$ and $H_{ii}^{L/R} = \text{diag}(4t_{L/R} + V_0, 4t_{L/R} + V_0)$ are the diagonal matrices. $\langle ij \rangle$ stands for the nearest-neighbor sites \mathbf{i} and \mathbf{j} , and $H_{ij}^{SC} = \text{diag}(-t_e, -t_e, t_h, t_h)$ and $H_{ij}^{L/R} = \text{diag}(-t_{L/R}, -t_{L/R})$ describe the nearest

neighbor hopping Hamiltonians. Here the hopping elements $t_{e/h} = \frac{\hbar^2}{2\gamma_{e/h}m_0a^2}$ and $t_L = t_R = \frac{\hbar}{2m_0a^2}$ with the discretized lattice constant a . The coupling Hamiltonians $H_{LC} = H_{RC} = \begin{pmatrix} t_c & 0 & t_c & 0 \\ 0 & t_c & 0 & t_c \end{pmatrix}$. After discretizing the Hamiltonian, by using the non-equilibrium Green's function method, the transmission coefficients $T_\sigma = \text{Tr}(\mathbf{\Gamma}_L \mathbf{G}^r \mathbf{\Gamma}_R \mathbf{G}^a)$ can be obtained straightforwardly.^{40,41} In the following calculations, we take the FM semiconductor's width $W = 20nm$ and length $5nm$, and the lattice constant $a = 0.1nm$. The gap is set at $E_g = 0.5eV$, $\gamma_e = \gamma_h = 1$ and $t_L = t_R = t_e = t_h = t_c$.

Fig. 3(c) shows the spin current I_s versus the spin bias V_s at different FM magnetization M in the presence of the interface scattering. Due to the interface scattering, I_s is slightly smaller than the ideal case. However, the spin-current diode feature holds well with a non-zero M : a large spin current appears in the forward spin bias but the reverse spin current is very small with the reverse spin bias. Furthermore, the five aforementioned characteristics are all maintained in the present case. At last, we consider the case of non-zero Fermi energy E_F (i.e. it is away from the particle-hole symmetric position). The Fermi energy can be tuned by the gate voltage in the experiment. While $E_F \neq 0$, $\mu_{L\uparrow} = eV_s + E_F$, $\mu_{L\downarrow} = -eV_s + E_F$ and $\mu_R = eV_R + E_F$. The results show that the threshold spin bias V_s^{th} slightly increases when E_F deviates from zero. But the spin-current diode features can survive when $E_F < E_g/2$, for example, the values of the forward spin currents are evidently larger than that of the reverse one for $E_F = 0.1eV$ and $0.15eV$ [see Fig. 3(d)]. Moreover, Fig. 3(d) shows that the spin current depends sensitively on the Fermi energy or gate voltage, a main function of a spin current transistor.

In conclusion, we predict that the lead/FM semiconductor (FM QD)/lead junction can work as the spin-current diodes, through which the forward spin current can easily flow while the reverse one is effectively blocked. In addition, the device discussed above can be easily fabricated, thus, the proposed spin-current diode is realizable with today's technology. The spin-current diode may have important applications in spintronics, just as the (charge-current) diode did in electronics.

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